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# **SINGLE AND MULTIPLE JET PENETRATION EXPERIMENTS INTO GEOLOGIC MATERIALS\***

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This paper presents the results of experiments that investigate the effect of single and multiple jet penetration into geologic materials. In previous studies of jet penetration into concrete targets, we demonstrated that an enhanced surface crater could be created by the simultaneous penetration of multiple shaped charge jets and that an enhanced target borehole could be created by the subsequent delayed penetration of a single shaped charge jet. This paper describes an extension of the multiple jet penetration research to limestone and granite.

## **INTRODUCTION**

This paper presents the results of experiments that investigate the effect of single and multiple jet penetrations into geologic materials. In previous work with concrete targets, we demonstrated that an enhanced surface crater could be created by the simultaneous penetration of multiple shaped charge jets and that an enhanced target borehole could be created by the subsequent delayed penetration of a unitary shaped charge jet [1-2]. Our current research extends this research to limestone and granite.

A first order principle of shaped charge jet penetration is that target hole volume is proportional to the energy deposited in the target by the jet and that target borehole diameter at any depth along the penetration path is proportional to the jet energy deposited in the target at that location [3-10]. The proportionality constant between jet energy deposited and target borehole diameter is a fundamental property of the target material while the influence of the penetrator material is a second order effect.

The primary focus of this work is on the effect of multiple jet penetrations into geologic materials with particular emphasis on increasing the target borehole volume. Unitary jet penetration experiments are first used to determine the jet energy – target hole volume relationship for tuff, limestone, and granite. Multiple jet penetration experiments into the same geologic materials are compared to the unitary charge results as well as to previous experiments into concrete with a discussion of the effects of target density, porosity, and strength.

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## SHAPED CHARGE DESCRIPTION

The XC-G1 charge (Fig.1) was used for the penetration experiments. It has a diameter of 12.7 cm with an l/d of 1. It has a thin aluminum case, plastic rear cover, detasheet/foam wave shaper for peripheral initiation and 2020g of LX-14 that produces a jet energy of  $1.32 \times 10^6$  joule. The aluminum liner was optimized to bore a cylindrical hole in concrete by delivering constant energy to the target during penetration. The "X-Charge" is similar to warheads used in previous studies at LLNL and elsewhere. [11-16]

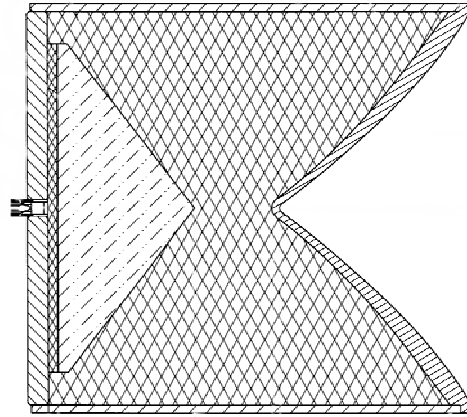


FIGURE 1. XC-G1 charge

## MAKING A SEMI-INFINITE TARGET REACT LIKE A FINITE TARGET

Our previous paper discussed how to make a semi-infinite target react like a finite target in the region of jet penetration [1]. The approach that we used was to create a finite target within a semi-infinite target as shown in Fig. 2. The damage to a semi-infinite target is the hole size created by the jet, which is proportional to the energy in the jet. The damage to a finite target is the whole target resulting in a higher proportionality to the energy in the jet. The cluster charge concept uses multiple shaped charges to create a finite target within a semi-infinite target by drilling holes and creating free surfaces around the path of a central jet penetrator.

In the cluster charge concept, the central jet penetrator is fired at the same time as the multiple jets. The penetration of the central jet links the multiple boreholes creating a single large hole. The cluster charge is more energy efficient for creating large boreholes in concrete and geologic materials. There is an increase in the diameter of the borehole with corresponding increase in total target borehole volume.

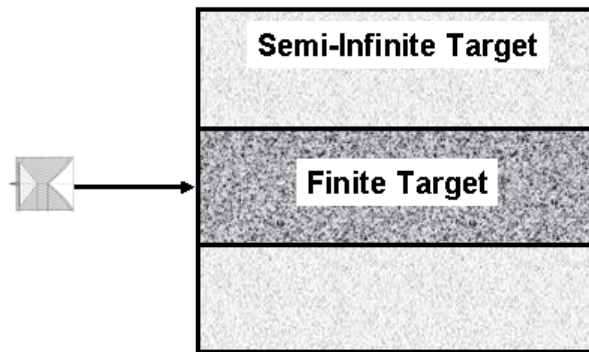


FIGURE 2. Finite target within the semi-infinite target.

## UNITARY JET TEST RESULTS

A summary of the hole size data for a unitary XC-G1 charge fired at 2 CD standoff into tuff, concrete, limestone, and granite is given in Table 2. The borehole profile (hole diameter versus depth) was measured along the penetration path using cylindrical probes of varying diameter. The total borehole volume was determined by summing the incremental volume between measurement points using the equation for the volume of a frustum of a cone. The energy per unit volume for the borehole is based on a calculated jet energy of  $1.32 \times 10^6$  joule. Note that for a unitary jet, the granite E/V (2409 J/cc) is almost three times larger than the high strength concrete E/V (882 J/cc).

TABLE 1. Hole size data for the XC-G1 charge fired into concrete and geologic materials

target material	borehole diameter top (cm)	borehole diameter bottom (cm)	penetration depth (cm)	borehole volume (cm <sup>3</sup> )	energy per unit volume (J/cc)
tuff-1	10.8	7.9	160.0	10280	128
tuff-2	6.7	4.1	139.7	3623	364
concrete	5.1	4.4	89.5	1497	882
limestone	4.3	2.6	76.2	668	1976
granite	3.5	2.2	74.3	548	2409

Photographs of the surface craters and entrance boreholes for jets fired at 2 CD standoff into concrete, limestone, and granite are shown in Fig. 3. Each of the frames has been sized so that the hole diameters are scaled. The 5.1 cm entrance borehole in concrete is reduced to 4.3 cm in limestone and then 3.5 cm in granite. Preliminary modeling studies suggest that the decreasing hole diameter may be more a function of the decreasing porosity of the materials rather than due to an increase in strength [17].

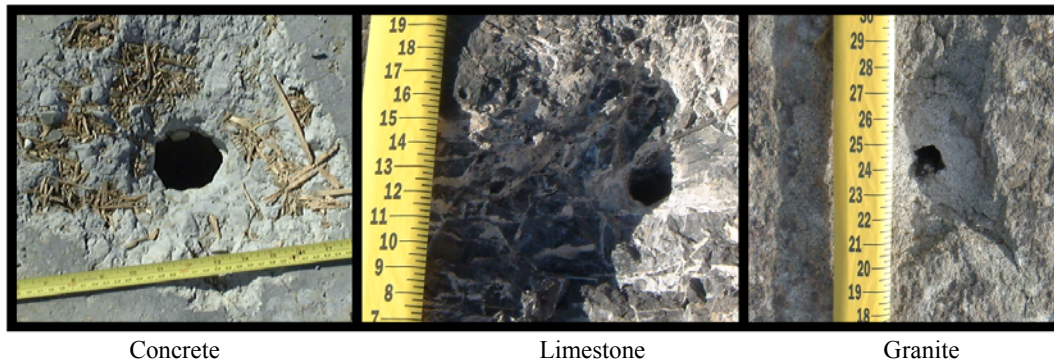


FIGURE 3. Photographs of surface craters and entrance boreholes from 1 jet at 2 CD standoff.

Plots of hole profiles from the XC-G1 jet fired at 2 CD standoff into concrete and the geologic materials are given in Fig. 4. The hole profiles (going from tuff to granite) indicate decreasing hole depth and smaller hole diameter. The decreases are assumed to be primarily due to a decrease in material porosity rather than an increase in material strength. A previous paper has shown the importance of using a porous material model for simulating the response of concrete and granite where we surmised the strength of in-situ weathered granite may be very similar to high strength concrete with a substantially lower porosity (2% vs. 12%) [17].

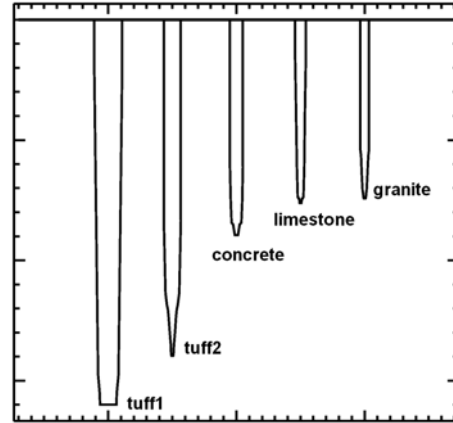


FIGURE 4. Hole profiles for the XC-G1 jet fired into concrete and geologic materials

## MULTIPLE JET TEST RESULTS

The prior multiple jet tests (four simultaneous jets) fired into concrete demonstrated an enhanced surface crater along with four distinct boreholes in the target [1]. The surface crater in concrete had a 300-mm square by 300-mm deep box-like structure. Similar results are obtained with the four XC-G1 jets into limestone (Fig. 5). However, in granite, four distinct boreholes from the four jets are not observed. Rather, the four boreholes have connected into one large square hole that is similar to the hole created by the penetration of four jets plus the delayed penetration of the central jet of a cluster charge. It is likely that the low porosity of granite is the cause of this behaviour.



FIGURE 5. Photographs of surface craters and entrance boreholes from 4 jets at 2 CD standoff.

## CLUSTER CHARGE TEST RESULTS

Our definition of the cluster charge is the combined effect of multiple peripheral jet penetrations followed by a central jet penetration. The effect is observed in both static and dynamic tests. In static tests, the central jet is not fired until after measuring the holes from the multiple jets. In dynamic tests, all charges are fired simultaneously. The dynamic tests produce similar results to the static tests but with slightly more target damage. Prior tests of four simultaneous jets plus one delayed jet fired into concrete demonstrated enhanced target borehole volume[1]. Similar results are shown in Table 2 for jets fired into limestone and granite. There are several important observations to note: a) the borehole size (lateral extent) from the cluster charge is the same for all of the target materials, b) the penetration depth is the same as the unitary charge penetration into each material, and c) the cluster charge is at least an order of magnitude more efficient at creating large volume boreholes in concrete and geologic materials (lower E/V). It is likely that the lateral extent of the borehole is primarily a function of the cluster charge geometry and shock wave interactions in the target from the penetration of the multiple jets. These results indicate that the cluster charge makes the same sized borehole independent of the strength and porosity of the target material.

TABLE 2. Hole size data for the XC-G1 charge fired into concrete and geologic materials

target material	borehole size top (cm)	borehole size bottom (cm)	penetration depth (cm)	borehole volume (cm <sup>3</sup> )	energy per unit volume (J/cc)
concrete	23 x 23	23 x 23	89.5	33600	39
limestone	23 x 23	23 x 23	76.2	28600	46
granite	23 x 23	23 x 23	74.3	27900	47



FIGURE 6. Photographs of surface craters and entrance boreholes from 4 jets plus 1 jet at 2 CD standoff.

## COMPARISON OF HOLE PROFILES

A comparison of target hole profiles in concrete, limestone, and granite for the unitary XC-G1 charge, a scaled unitary charge with five times the XC-G1 charge energy, and the cluster charge with five XC-G1 charges is shown in Fig. 7. The smallest diameter hole for each set of material hole profiles is from the tests conducted with the unitary XC-G1 charge. The largest hole size for each set of material hole profiles is from the tests conducted with a cluster of five XC-G1 charges (four peripheral jets plus one central jet). The middle hole profile is based on scaling the unitary XC-G1 charge hole crosssectional area by a factor of five. The is based on the assumption of a fictitious charge that delivers the same penetration depth as a unitary XC-G1 charge while delivering five times the energy during penetration (ie. a unitary charge with five time the energy as a single XC-G1 jet).

As discussed previously, it is interesting to note that the hole diameter from the unitary charge penetration is very dependent on target material while the hole diameter from the cluster charge penetration is almost independent of the target material.

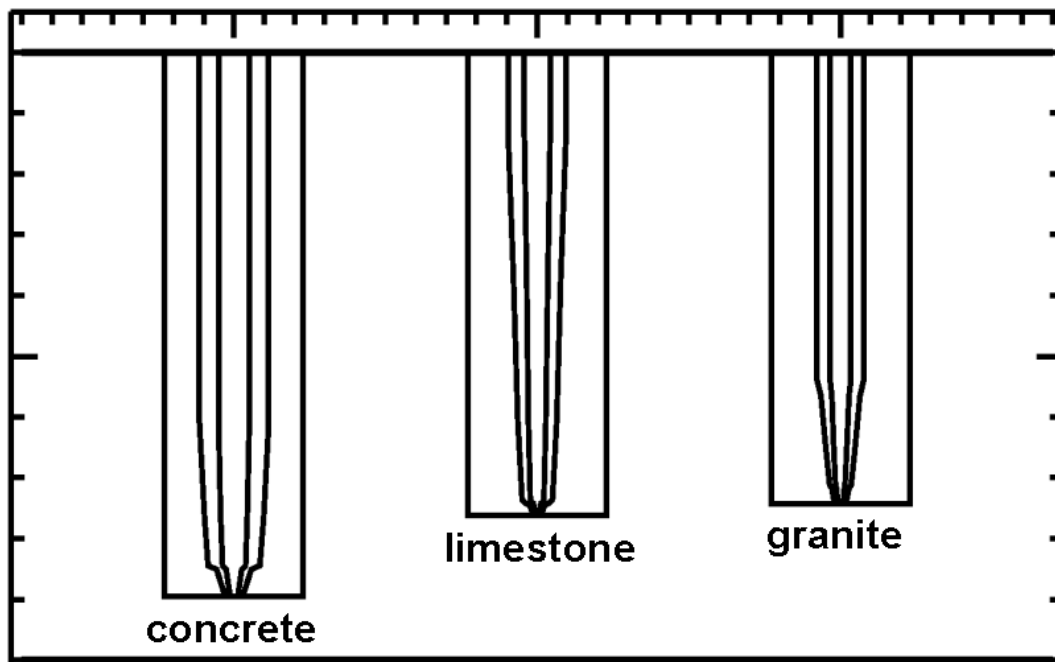


FIGURE 7. Unitary charge, scaled, and cluster charge hole profiles in concrete, limestone and granite.

## **SUMMARY AND CONCLUSIONS**

In previous jet penetration experiments into concrete targets, it was shown that an enhanced diameter borehole could be created in the target with the cluster charge. Our current research has demonstrated equivalent enhancement of the borehole diameter in geologic target materials using the cluster charge. Unitary jet penetration experiments into limestone and granite result in smaller borehole diameters than achieved in concrete while cluster charge jet penetrations into limestone and granite produce the same borehole diameter as in concrete.

The target hole profile and volume resulting from a unitary jet penetration is predictable with standard modeling methods. First order principles indicate the borehole volume is proportional to the jet energy deposited in the target. Our work from 20 years ago combined with the current data indicates the E/V constant for concrete ranges from 700-900 J/cc depending on the target material compressive strength. Unitary jet penetration experiments conducted into geologic materials indicate an E/V constant of about 2000 J/cc for limestone and 2400 J/cc for granite. The E/V constant for the cluster charge penetration into concrete, limestone, and granite ranges from 39 J/cc to 47 J/cc. Several conclusions we have drawn from these results are listed below:

- 1) The results indicate that the cluster charge is more than an order of magnitude more energy efficient at creating large volume boreholes than a unitary shaped charge.

- 2) The results indicate that boreholes created in concrete and geologic materials with the cluster charge are independent of the strength and porosity of the target. the cluster charge makes about the same sized borehole in granite and limestone as it does in concrete.

- 3) It is our opinion that the lateral extent of the borehole is primarily a function of the cluster charge geometry and shock wave interactions in the target from the penetration of the multiple jets.

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